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MULTIPLE COHERENCE OF NOISE AT 3 VERTICAL ARRAYS UBSO, GV-TX, AP-OK

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MULTIPLE COHERENCE OF NOISE
AT 3 VERTICAL ARRAYS
UBSO, GV-TX, AP-OK

SEISMIC DATA LABORATORY REPORT NO. 191

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ABSTRACT

Multiple coherence gives a quantitative measure versus frequency of how well a linear combination of n input channels can match the (n + 1)st channel in a seismic array. If the inputs can match the output exactly, then the multiple coherence is unity and only n channels are necessary to describe the noise field. This report shows multiple coherence versus frequency at three vertical arrays of short period, vertical component seismometers. One of the seismic traces, either the surface trace or the deepest trace, is used as the output and 2 to 6 of the others are used as inputs.

The multiple coherence properties of the noise are similar at the three vertical arrays with similar geometries. At all three sites the downhole channels correlate with each other better than with the surface channel. At all three sites the coherence between downhole seismometers decreases markedly as their separation increases.

When the deep trace is the output and all seismometers are added as inputs, the multiple coherence is highest at GV-TX. The multiple coherence at GV-TX is greater than .85 for all frequencies from .1 to 2.5 cps. For the AP-OK and UBSO wells the multiple coherence varies between .6 to .9 for most frequencies greater than .5 cps.

1. INTRODUCTION

Most basic data processing techniques for signal enhancement or identification depend upon the structure of the noise within the seismic array. If some of the coherent noise is due to site characteristics such as consistently coherent noises from particular directions, then techniques using multiple coherence will help to isolate these consistent linear relations. Many optimum filters for estimating the signal take account of these linear relations implicitly by weighting with the inverse of the spectral noise matrix. However, one cannot tell whether the coherent noise involved is due to noise generating events which cannot be predicted or controlled. Thus, the filters must be recalculated over a period of noise recording immediately prior to the arrival of each single signal. Part of the coherent noise generated within the array may be due to various causal factors for a particular array. If so, we can learn something about these factors by examining the linear relations between the various array elements. A potential benefit here is that a consistent linear model relating the different sub-elements would eliminate the need for computing a different set of filter coefficients for each event.

The multiple coherence function can indicate how many seismometer outputs in an array are necessary to properly determine the seismic noise field. If there are n independent seismic noise components, then the multiple coherence function would be unity when (n + 1)st seismometers are placed in an array to measure seismic noise records. If part of the background is

composed of incoherent noise, then the multiple coherence function would indicate the percentage of coherent noise present and the number of seismometers necessary to define this coherent noise. The filter relations determined by the multiple coherence computations can then be used in array summation to bring the noise into destructive interference.*

This analysis does not guarantee that such optimum processing is possible. For example, if the noise and signal propagation characteristics across the array are identical, no velocity filtering scheme can be expected to separate the two even though the multiple coherence might be unity.

The multiple coherence function is the frequency domain equivalent of the prediction error filter in time. If n input seismic traces predict the (n + 1)st trace in an array completely, then the multiple coherence will be unity and a prediction error filter could be used to exactly predict this (n + 1)st output. In fact, linear filter relations derived by the multiple coherence program produce an estimate of the (n + 1)st trace which, when subtracted from the actual (n + 1)st trace, given a prediction error trace. Thus the comination of the filter derived in the multiple coherence program and the subtraction operation produces a prediction error filter as shown in the following diagram.

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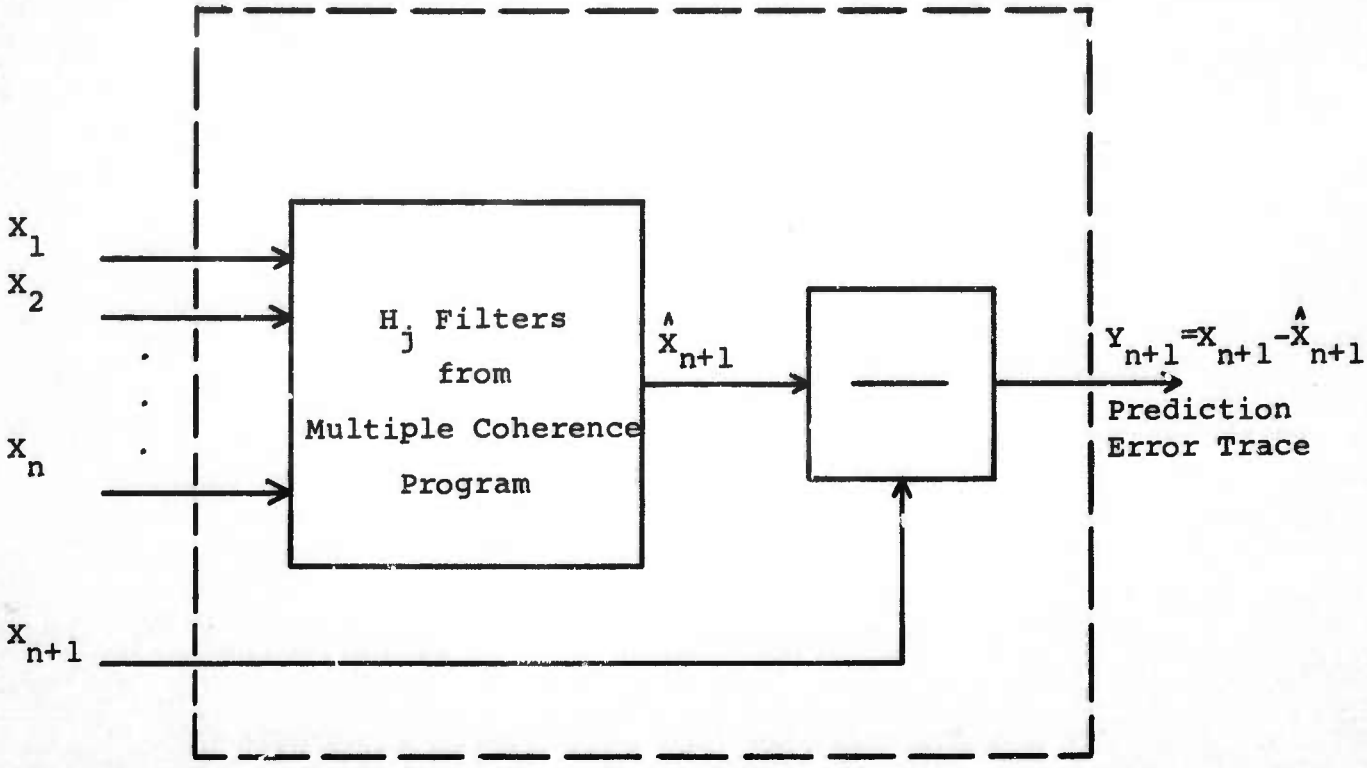
*For the mathematical description of the multiple coherence computation see Appendix I.



Prediction Error Filter

The objective of this study is to use the multiple coherence function to estimate the degree of predictability of the short period noise field at three deep well sites; UBSO, GV-TX and AP--OK.

2. DESCRIPTION OF DATA

We computed the multiple coherence of short period vertical component data from three vertical arrays. The first is at UBSO and includes a near-surface instrument in a 250 foot hole located 4000 feet from the well, plus six downhole instruments from 4000 to 9000 feet. The second is from GV-TX and includes a surface instrument at the well plus six downhole instruments from 4500 to 9500 feet. The third is from AP-OK and includes a surface instrument at the well plus one at 50 feet and four downhole instruments from 5500 to 9500 feet.

The sampling rate for the data is 10 samples per second. The number of points in the samples vary but are all between 3 to 3.5 minutes. The frequency range is from 0.1 to 2.6 cps with a frequency increment of 0.1 cps.

We varied the number of input channels in our multiple coherence computations from 2 to 6. We grouped the seismometers in two ways. For one group we used the surface instrument as the output and the other instruments as inputs. For the second group we used the bottom instrument as output channel and the other six as inputs. In each case the inputs furthest from the output channel were added first.

We examined two noise samples each from UBSO and AP-OK and one noise sample from GV-TX. At AP-OK one sample was long enough to make three successive samples of 3.5 minutes. All stationarity computations were made on these samples.

3. RESULTS

Multiple Coherence

On all of the multiple coherence plots in this report the output trace is either from the surface seismometer or the deepest seismometer. The ordering of the input channels starts with the furthest seismometers away from the output. On each of the multiple coherence plots a diagram of the instrument locations in the vertical array for that site is shown on the lower right. The inputs are listed in order of their addition to the multiple coherence computations.

Figure 1 shows multiple coherence versus frequency for the two output cases from data recorded at UBSO on 3 December 1966. The upper diagram shows multiple coherence with a surface instrument as output. The multiple coherence over most of the frequency range is generally low. Even at the microseismic frequencies (0.2 to 0.5 cps) the multiple coherence is less than .6 with all six downhole instruments used as inputs. This result shows that none of the downhole instruments correlate very well with the surface instrument. An exception occurs at 1.9 cps where the multiple coherence is high even for two inputs.

The lower diagram shows the multiple coherence with the deepest instrument as output. The multiple coherence is high throughout most of the frequency range, and especially so for 4 and 5 inputs when the deepest instrument is the output channel. The strong coherence at 1.9 cps shows up again but is not so evident since coherence at other frequencies is also

high. The multiple coherence increases with increasing number of inputs. The last inputs added are the ones closest to the output (deepest) seismometers. Over the range 1.0 to 1.8 cps correlation is high between seismometers separated by 2000 and 4000 feet but decreases considerably for seismometers separated by 6000 feet or more.

Figure 2 shows multiple coherence versus frequency for the two output cases on 7 January 1967. As in Figure 1, the upper diagram uses the surface instrument as the output and the lower diagram uses the deepest instrument as the output. The results in Figures 1 and 2 agree everywhere except that the highly correlated noise at 1.9 cps is not present on the 7 January 1967 sample.

Figure 3 shows multiple coherence versus frequency for data recorded at GV-TX on 20 March 1965. Again the upper diagram uses the surface seismometer as output and the lower diagram uses the deepest seismometer as output. The downhole traces at GV-TX correlate well with the surface trace for the microseisms (0.2 to 0.5 cps) especially with 3 or more inputs. However, the correlation of the downhole traces with the surface trace over the remainder of the frequency range is low.

With the deepest trace as output the multiple coherence with all 5 inputs is high (about 0.9) throughout the entire frequency range (0.1 to 2.6 cps). The multiple coherence increases significantly as inputs closer to the output are added. Furthermore, the multiple coherence at GV-TX with closest input 2000 feet from the output seismometer (the 4 input case) agrees

closely with the final multiple coherence for UBSO where the closest input is 2000 feet from the output seismometer. Thus coherence over the signal band in these vertical arrays decreases with increasing seismometer separation with very strong coherence for separation of only 1000 feet.

Figure 4 shows multiple coherence at AP-OK using surface trace as output for two time samples 3½ minutes long with a 3 minute gap between them. The multiple coherence for the microseismic band (0.2 to 0.5 cps) is high for any number of inputs. The multiple coherence over the signal band (1.0 to 1.5) cps is low for 4 inputs or less. There is a significant increase in multiple coherence at 1.7 cps. When the last input trace, only 50 feet from the output surface seismometer, is added, the multiple coherence becomes high (greater than 0.9) for all frequencies. These two traces are recording essentially the same data.

Figure 5 shows multiple coherence using the deepest trace as output for the same neighboring time samples shown in Figure 4. The results on Figure 5 agree with those on Figure 4 with two exceptions. The first is that the final multiple coherence does not stay above 0.9 everywhere since no input is closer than 2000 feet to the output. The second is that larger multiple coherence occurs over the signal band (1.0 to 1.5 cps) than in Figure 4 showing that the downhole traces correlate with each other more than with the surface trace.

Figure 6 shows similar multiple coherence using a surface trace and a deepwell trace as outputs for AP-OK data recorded on 12 May 1965. In both examples the multiple coherence is low until the closest seismometer to the output seismometer is added to the inputs.

Figures 7, 8, and 9 show the ranges for input and output power spectra for the UBSO, GV-TX and AP-OK vertical arrays respectively. The spectra from all of these wells show a significant noise peak near 2 cps.

Stationarity Tests

Figures 10 and 11 show the expected db reduction in noise when prediction error filters are applied to three successive samples of 3 minutes each recorded at AP-OK. Figure 10 uses the deepest instrument as output. Figure 11 uses the surface instrument as output. Over the microseismic band (0.2 to 0.5 cps) the expected noise reduction inside the fitting interval varies between 16 and 22 db and outside the fitting interval within 2 db of this value. Over the signal band the expected noise reduction is less varying between 8 and 14 db when the deep instrument is output and between 2 and 7 db when the surface instrument is output within the fitting interval. The expected noise reduction is nearly as good outside the fitting interval. The strong correlations near 2 cps show expected noise reductions and stationarity properties similar to the noise in the signal band.

These tests show that the noise correlation in vertical arrays is much higher than correlations over surface arrays. Over three successive noise samples, at least, the noise seems to be strong. The stationarity test again shows that the deep instrument correlates with the others better than the surface instrument since the expected noise reduction is greater with the deep instrument as output.

4. CONCLUSIONS

1. The multiple coherence properties of the noise at the three vertical arrays with similar geometries are similar. At all three sites the downhole channels correlate with each other better than with the surface channel. At all three sites the coherence between downhole seismometers decreases markedly as their separation increases.

2. When the deep trace is the output and all seismometers are added as inputs, the multiple coherence is highest at GV-TX. In fact it is greater than .85 for all frequencies from .1 to 2.5 cps. For the AP-OK and UBSO wells the multiple coherence varies between .6 to .9 for most frequencies greater than .5 cps.

3. All three sites show a significant 2 cps component in the noise spectra for most of the examples tested. The multiple coherence of this 2 cps component is high but not appreciably higher than other noise frequencies above the microseismic band. Even the surface trace correlates well with the downhole traces for the 2 cps component.

4. The noise at AP-OK appears to be more stationary than noise at surface arrays. For three successive 3½ minute samples the expected noise reduction from a prediction error filter applied in the fitting interval was 16 to 20 db over the microseismic band and between 2 and 7 db for frequencies greater than 0.5 cps. Outside the fitting interval the expected noise reduction was within 2 db of these values.

FIGURES

1. Multiple coherence versus frequency for a UBSO sample recorded in December 1966. The upper diagram uses the surface instrument as output; the lower uses the deepest instrument as output.

2. Multiple coherence versus frequency for a UBSO sample recorded in January 1967. The upper diagram uses the surface instrument as output; the lower uses the deepest instrument as output.

3. Multiple coherence versus frequency for a GV-TX sample recorded in March 1965. The upper diagram uses the surface instrument as output; the lower uses the deepest instrument as output.

4. Multiple coherence versus frequency at AP-OK for two samples 3 minutes apart. The surface instrument is the output.

5. Multiple coherence versus frequency at AP-OK for the same samples shown in Figure 4 but with the deepest instrument as the output.

6. Multiple coherence versus frequency at AP-OK for a sample recorded in May 1965. The upper diagram uses the surface instrument as output; the lower uses a deep instrument as output.

7. The output and range of input power spectra for samples recorded at UBSO in December 1966.

8. The output and range of input power spectra for samples recorded at GV-TX in December 1966.

9. The output and range of input power spectra for samples recorded at AP-OK in December 1966.

10. Expected db reduction in noise when prediction error filters are applied to three successive samples at AP-OK. The fitting interval is the Time 1 sample. The deepest instrument is output.

11. Expected db reduction in noise when prediction error filters are applied to three successive samples at AP-OK. The fitting interval is the Time 1 sample. The surface instrument is output.

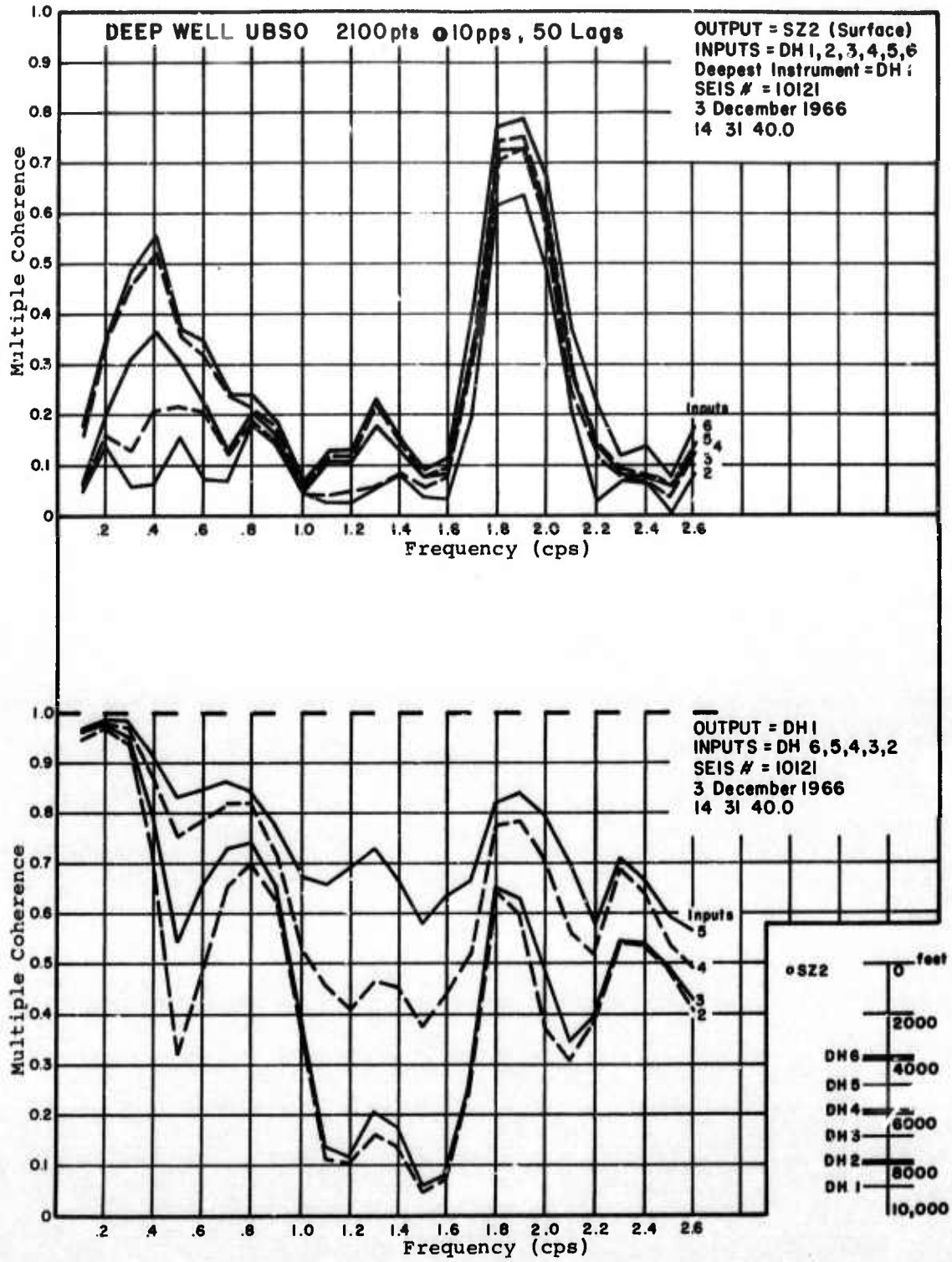


Figure 1. Multiple coherence versus frequency for a UBSO sample recorded in December 1966. The upper diagram uses the surface instrument as output; the lower uses the deepest instrument as output.

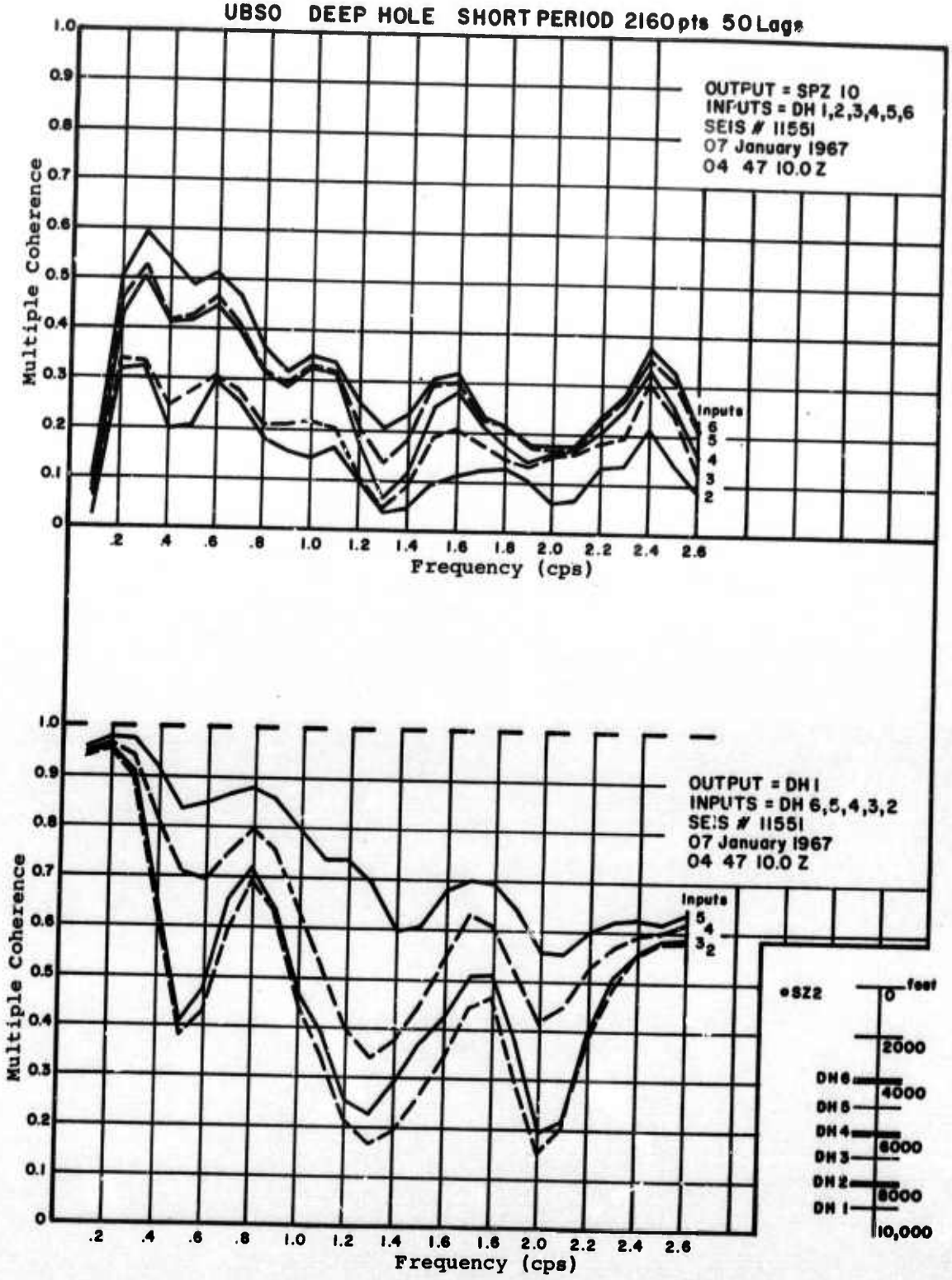


Figure 2. Multiple coherence versus frequency for a UBSO sample recorded in January 1967. The upper diagram uses the surface instrument as output; the lower uses the deepest instrument as output.

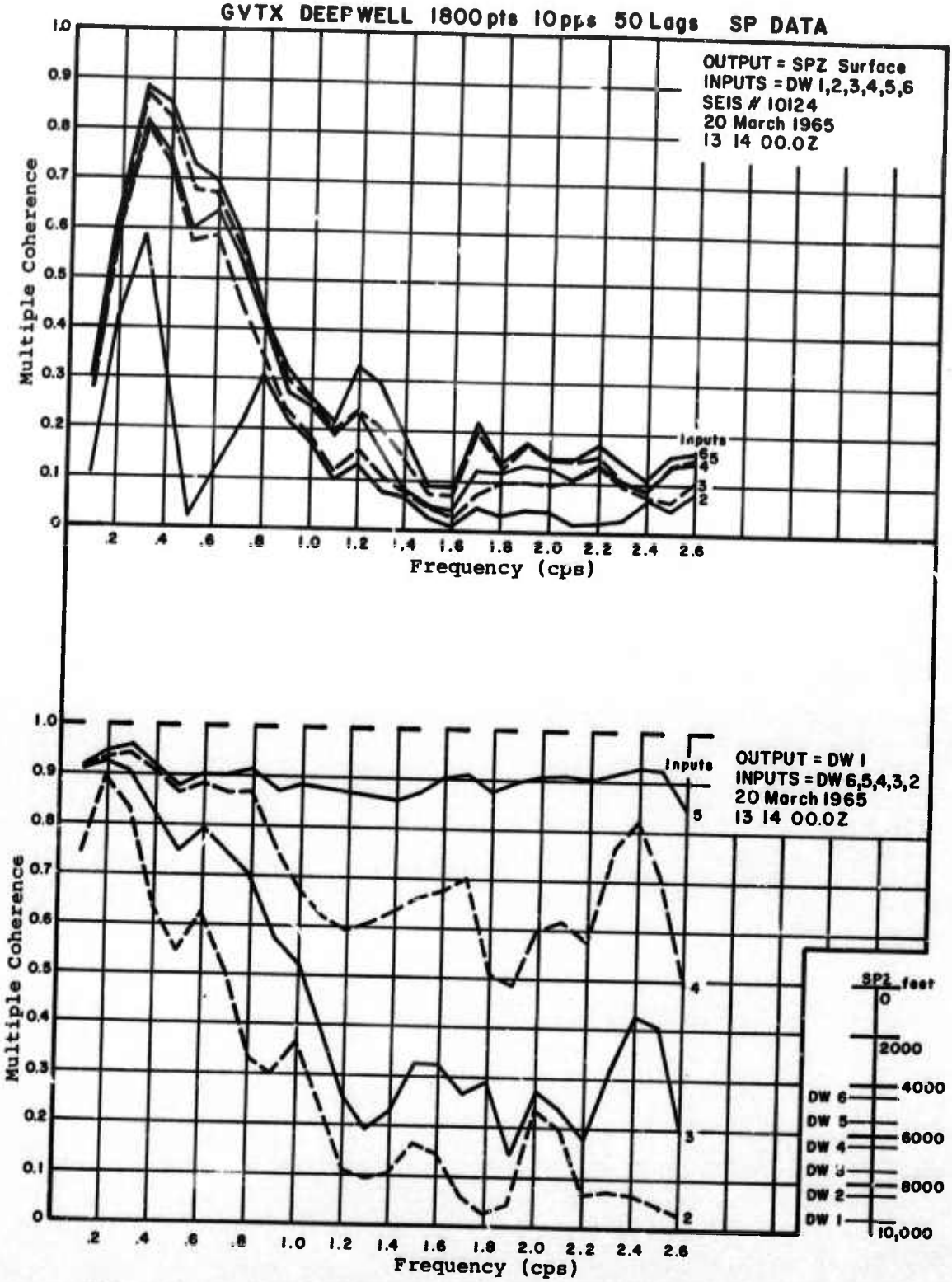


Figure 3. Multiple coherence versus frequency for a GV-TX sample recorded in March 1965. The upper diagram uses the surface instrument as output; the lower uses the deepest instrument as output.

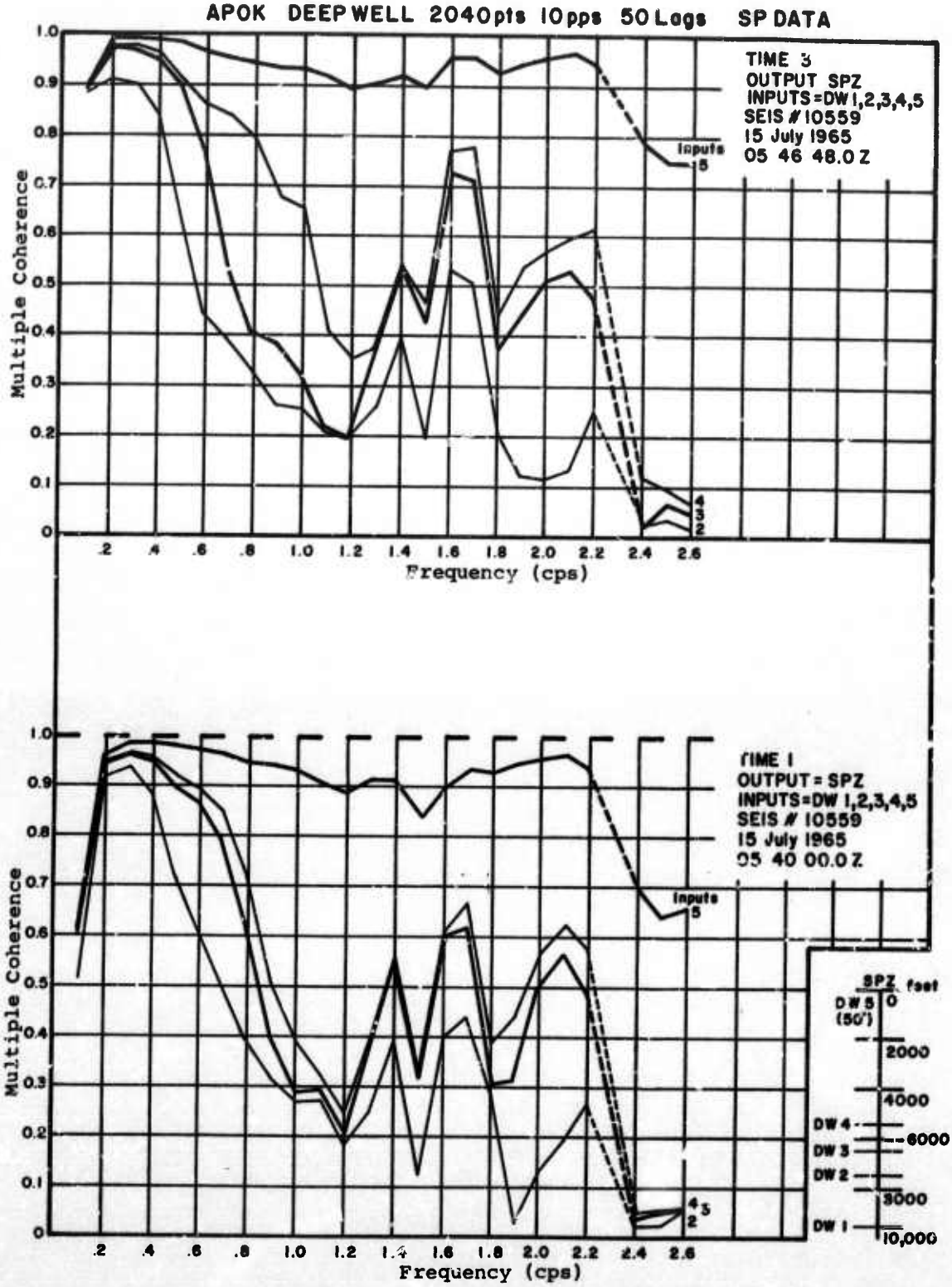


Figure 4. Multiple coherence versus frequency at AP-OK for two samples 3 minutes apart. The surface instrument is the output.

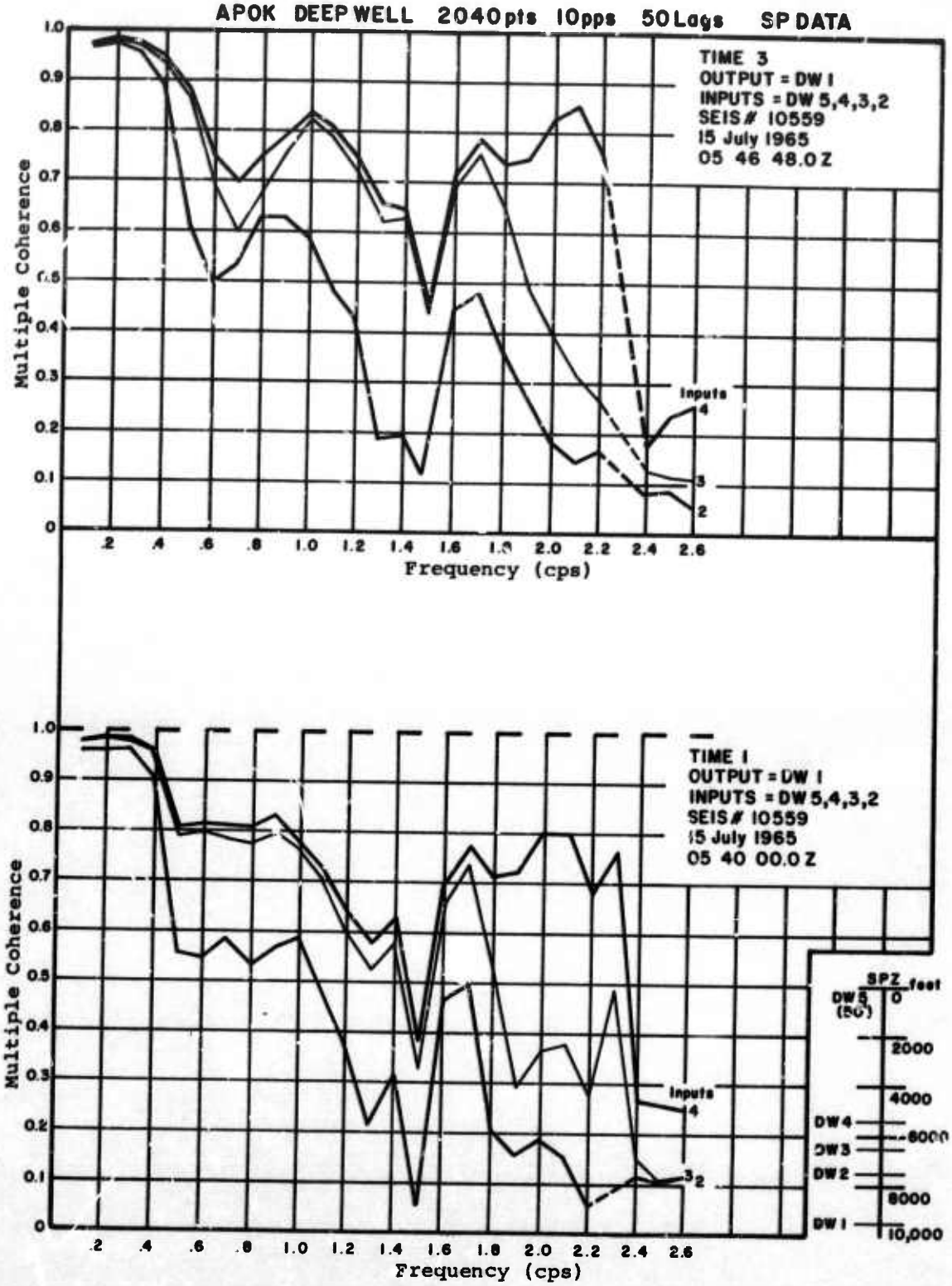


Figure 5. Multiple coherence versus frequency at AP-OK for the same samples shown in Figure 4 but with the deepest instrument as the output.

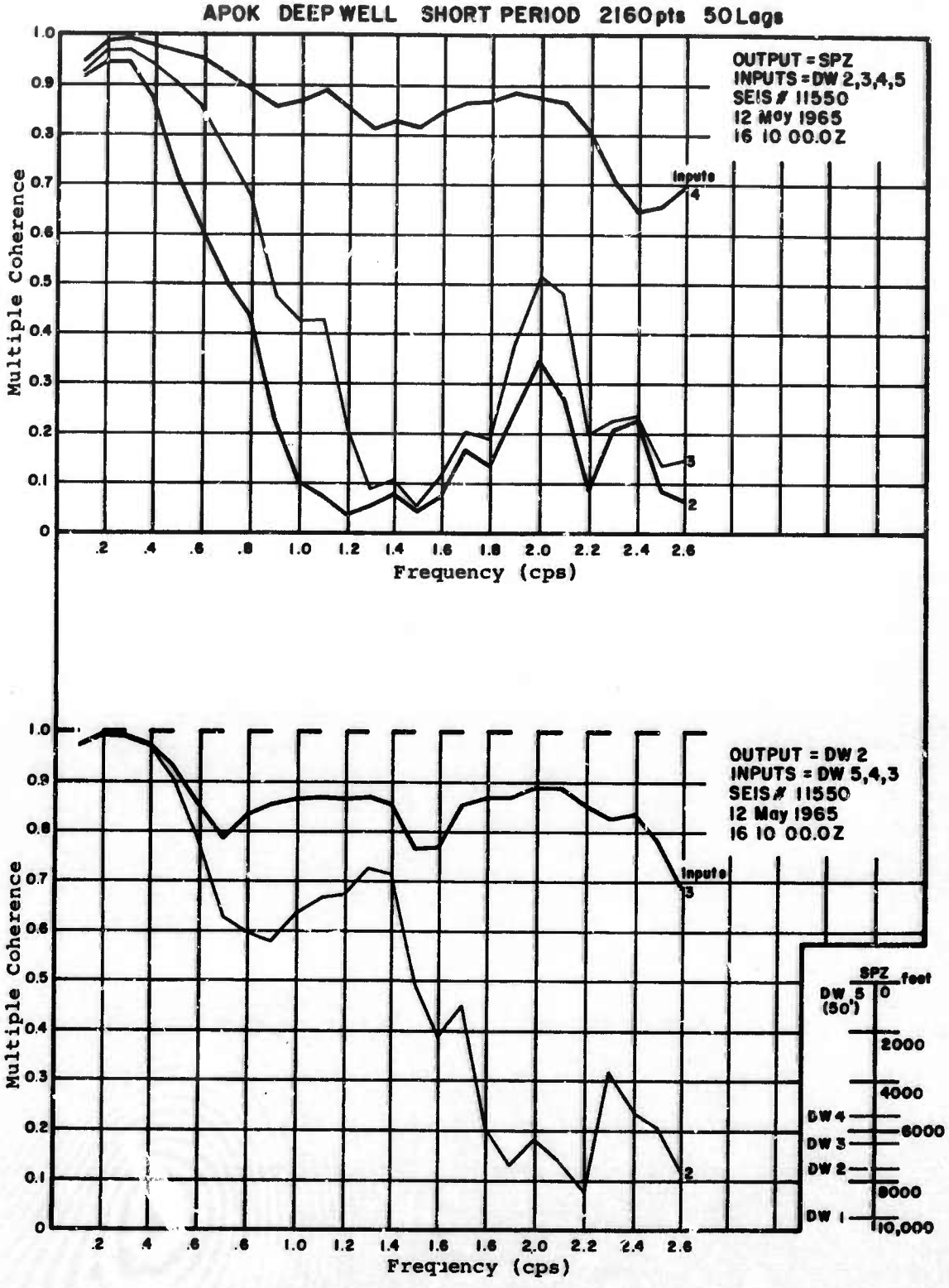


Figure 6. Multiple coherence versus frequency at AP-OK for a sample recorded in May 1965. The upper diagram uses the surface instrument as output; the lower uses a deep instrument as output.

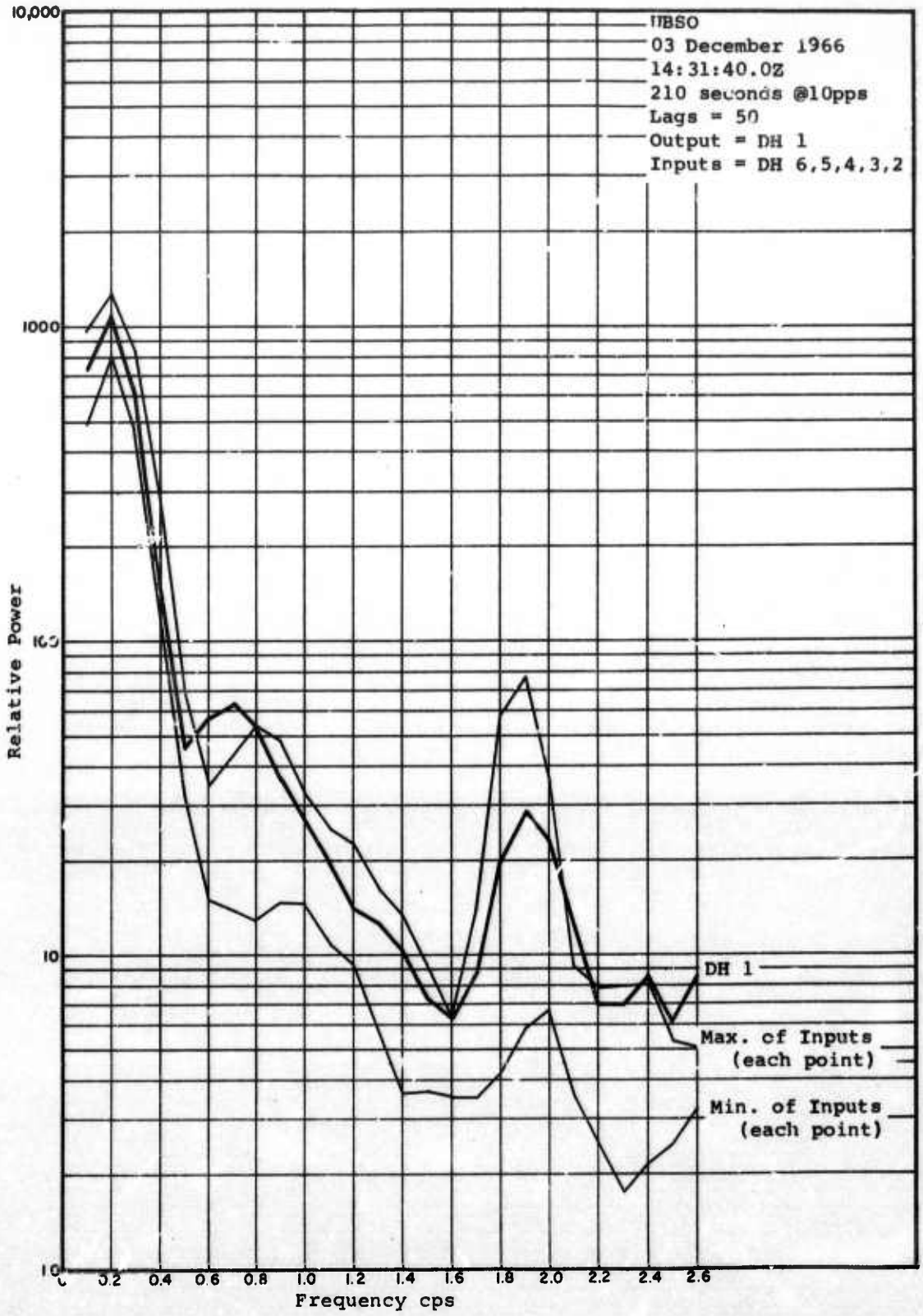


Figure 7. The output and range of input power spectra for samples recorded at UBSO In December 1966.

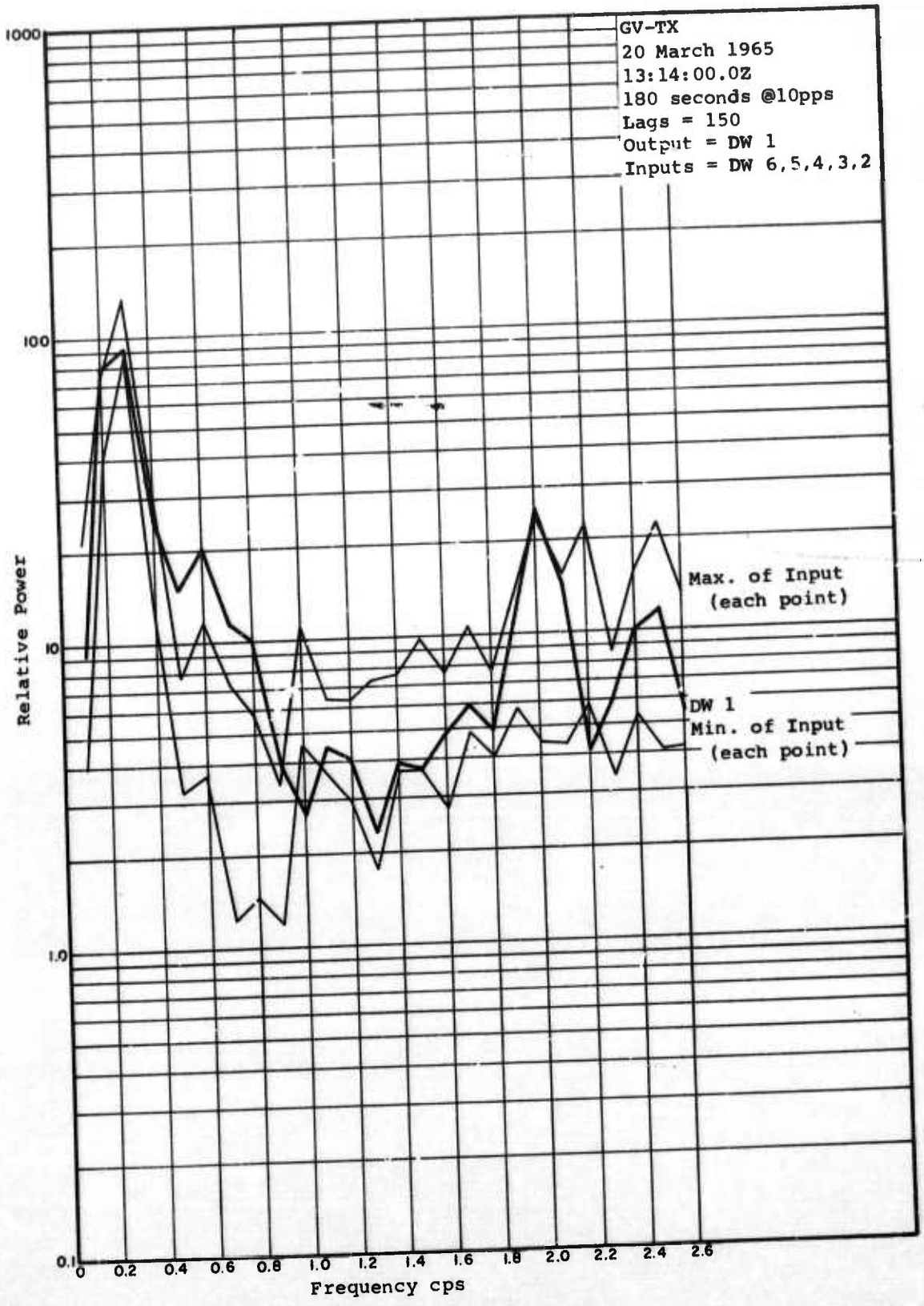


Figure 8. The output and range of input power spectra for samples recorded at GV-TX in December 1966.

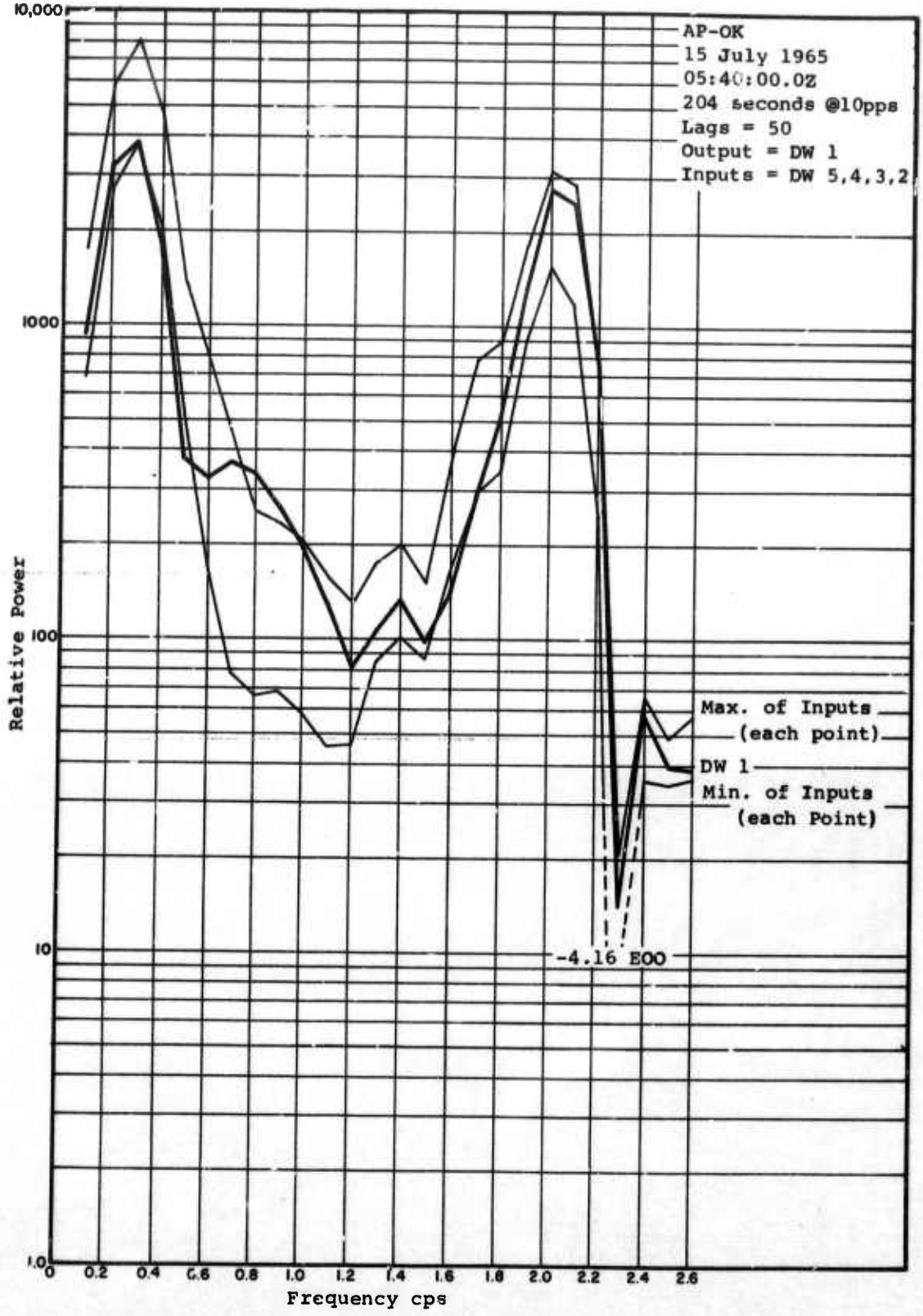


Figure 9. The output and range of input power spectra for samples recorded at AP-OK in December 1966.

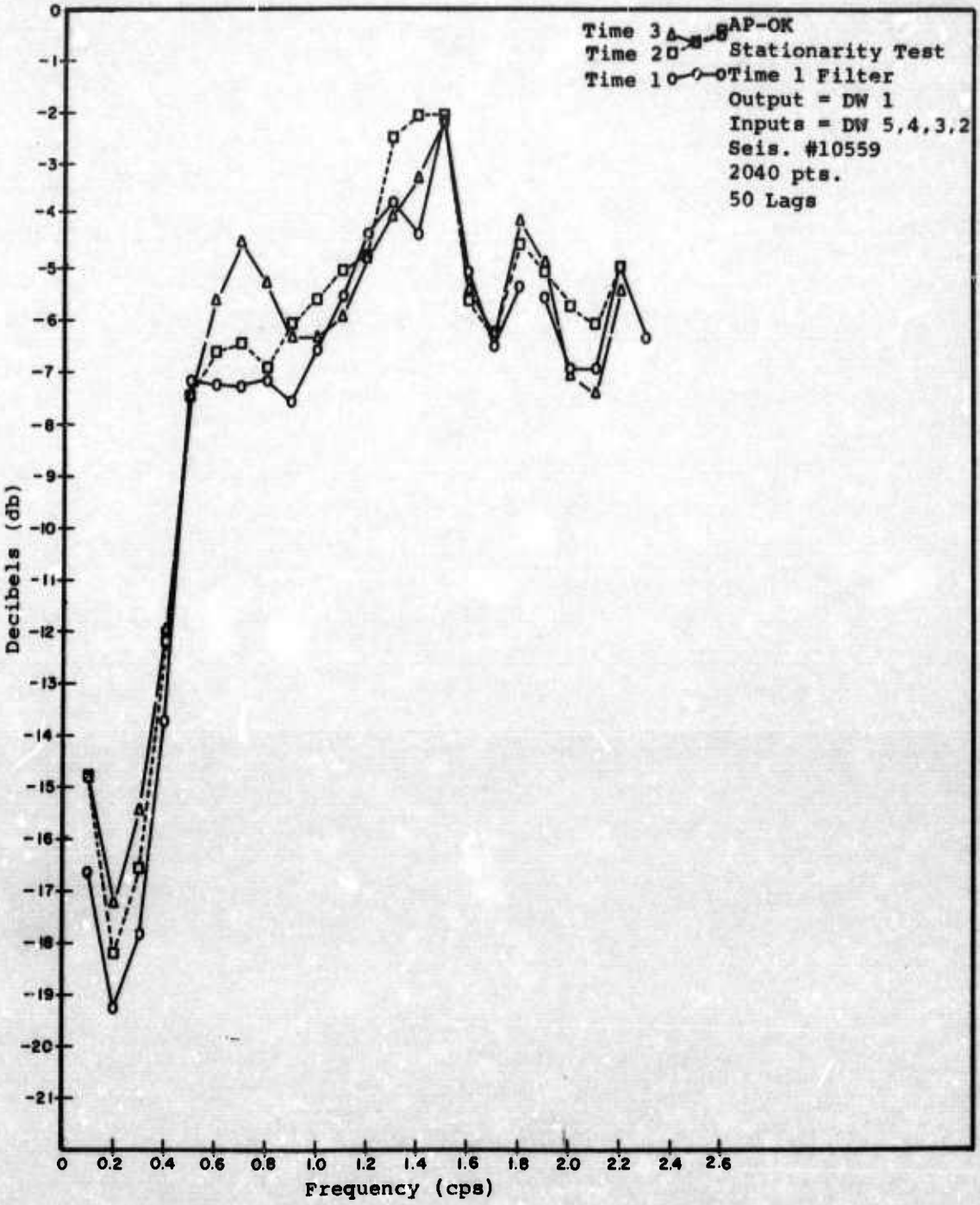


Figure 10. Expected db reduction in noise when prediction error filters are applied to three successive samples at AP-OK. The fitting interval is the Time 1 sample. The deepest instrument is output.

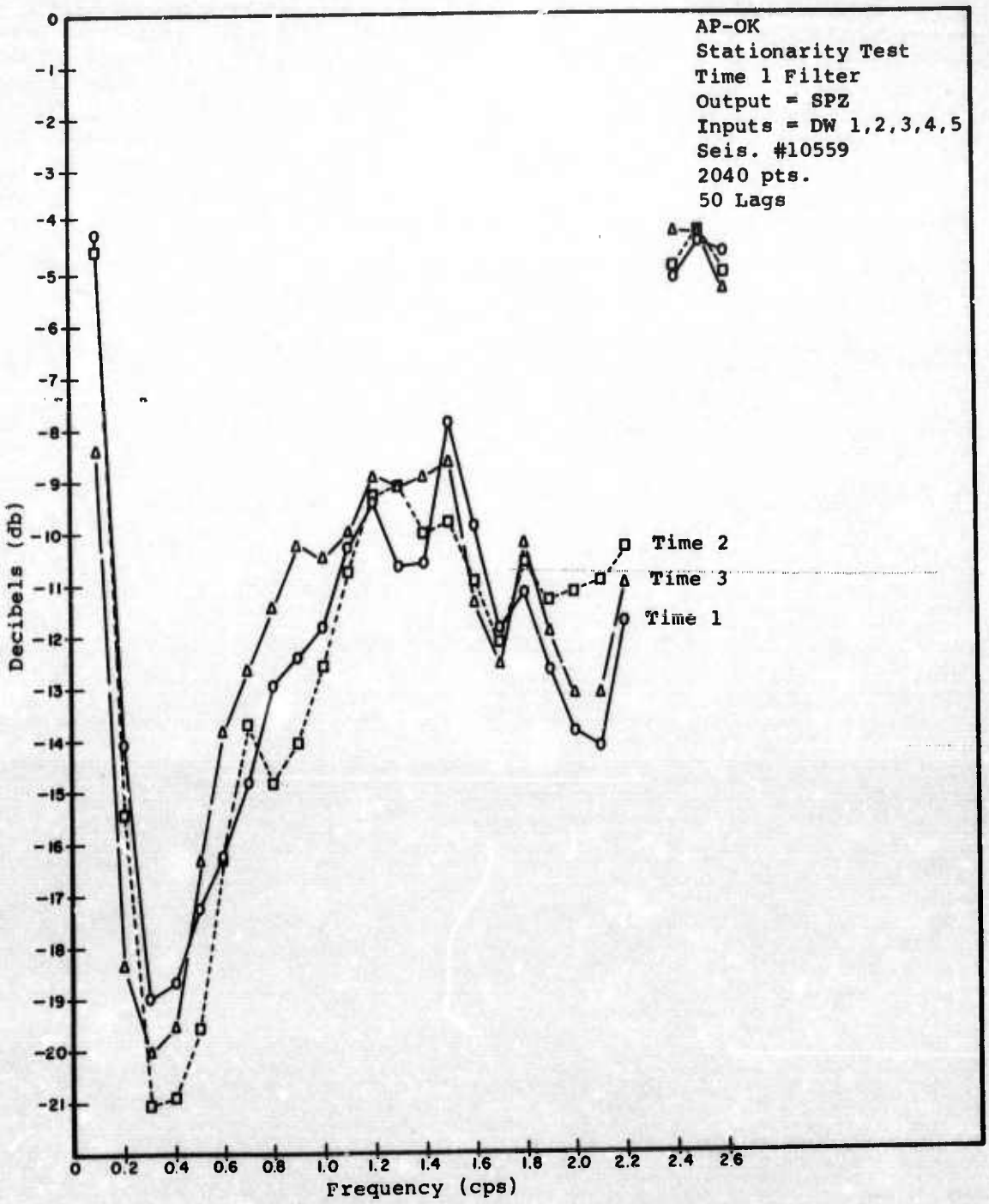


Figure 11. Expected db reduction in noise when prediction error filters are applied to three successive samples at AP-OK. The fitting interval is the Time 1 sample. The surface instrument is output.

APPENDIX I

*Multiple Coherence Functions

Consider a collection of q clearly defined inputs $x_i(t)$; $i = 1,2,\ldots,q$, and one output $y(t)$, as pictured in Figure 5.12. Let $G_i(f) = G_{ii}(f)$ be the

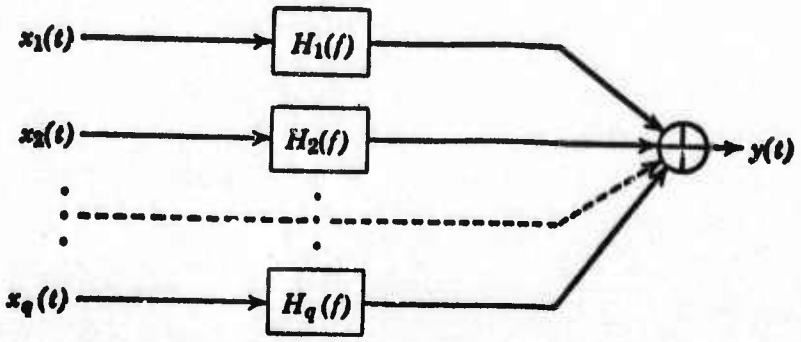


Figure 5.12 Multiple-input linear system.

power spectral density function for $x_i(t)$, and $G_{ij}(f)$ be the cross-spectral density function between $x_i(t)$ and $x_j(t)$. Define the N x N spectral matrix by

$$G_{xx}(f) = \begin{bmatrix} G_{11}(f) & G_{12}(f) & \cdots & G_{1q}(f) \\ G_{21}(f) & G_{22}(f) & & G_{2q}(f) \\ \vdots & & & \\ G_{q1}(f) & G_{q2}(f) & & G_{qq}(f) \end{bmatrix} \qquad (1)$$

*This explanation of multiple coherence functions was taken from "Measurement and Analysis of Random Data", Bendat, J. S., and Piersol, A. G., John Wiley and Sons, 1966. For more detailed theoretical developments and discussions of multiple, partial and marginal coherence functions, see this text.

The ordinary coherence function between $x_i(f)$ and $x_j(t)$ is defined by

$$\gamma_{ij}^2(f) = \frac{|G_{ij}(f)|^2}{G_i(f)\, G_j(f)} \tag{2}$$

The multiple coherence function between $x_i(t)$ and all other inputs $x_1(t)$, $x_2(t)$,...,excluding $x_i(t)$, is defined by

$$\gamma_{i,m}^2(f) = 1 - [G_i(f)\, G^i(f)]^{-1} \tag{3}$$

where $G^i(g)$ denotes the ith diagonal element of the inverse matrix $G_{xx}(f)^{-1}$ associated with Eq. (1). The ordinary and multiple coherence functions are both real-valued quantities which are bounded by zero and unity. That is,

$$\begin{aligned} 0 \le \gamma_{ij}^2(f) \le 1 \\ 0 \le \gamma_{i,m}^2(f) \le 1 \end{aligned} \tag{4}$$

The multiple coherence function is a measure of the linear relationship between the time history at one point, and the time histories at the collection of other points. That is, the multiple coherence function indicates whether or not the data at all of the other points linearly produce the results at a given point.

APPENDIX 2

Theoretical Development of The Stationarity Relations

A. Noise Reduction Within The Fitting Interval

A number of useful statistical measures such as ordinary and multiple coherence can be used as tools to indicate the amount of noise reduction feasible in a multiply coherent array. The basic linear model which determines the db reduction possible in the noise field by multiple coherence filtering relates a reference element (trace) $y(t)$ of an array to the other elements, say $x_1(t)$, $x_2(t)$, ..., $x_p(t)$ in the array through the linear model

$$y(t) = \sum_{k=1}^{p} \int_{-\infty}^{\infty} h_k(\alpha)\, x_k\,(t-\alpha)\, d\alpha \qquad (1)$$

Generally we determine $h_k(t)$ as the time invariant linear filter that makes the mean square error between $y(t)$ and its predicted value a minimum, i. e.

$$E \left| y(t) - \sum_{k=1}^{p} \int_{-\infty}^{\infty} h_k\,(\alpha)\, x_k(t-\alpha)\, d\alpha \right|^2 = \min \qquad (2)$$

which, by the usual orthogonality principle (see Papoulis 1), yields the condition

$$Ey(t)\, x_\ell(t+\tau) = \sum_{k=1}^{p} \int h_k(\alpha)\, E\, x_k\,(t-\alpha)\, x_\ell\,(t+\tau)\, d\alpha$$

$$\ell = 1,2, \ldots, p, -\infty<\tau<\infty \qquad (3)$$

or

$$R_{yx_\ell}(\tau) = \sum_{k=1}^{p} \int h_k(\alpha)\, R_{x_k x_\ell}(\tau+\alpha)\, d\alpha \qquad (4)$$

which by taking Fourier transforms implies that

$$S_{yx\ell}(\omega) = \sum_{k=1}^{p} H_k^*(\omega)\, S_{x_k x_\ell}(\omega) \qquad (5)$$

Now, the mean square error can be written

$$E\left|y(t) - \sum_{k=1}^{p} \int h_k(\alpha)\, x_k(t-\alpha)d\alpha\right|^2 = E\left(y(t) - \sum_{k=1}^{p} \int_{-\infty}^{\infty} h_k(\alpha)x_k(t-\alpha)d\alpha\right) y(t)$$

$$= R_{yy}(0) - \sum_{k=1}^{p} \int h_k(\alpha)\, R_{x_k y}(\alpha)\, d\alpha$$

$$= \int_{-\infty}^{\infty} \left[S_{yy}(\omega) - \sum_{k=1}^{p} H_k^*(\omega)\, S_{x_k y}(\omega)\right] \frac{d\omega}{2\pi}$$

$$= \int_{-\infty}^{\infty} \left(S_{yy} - \underline{S}_{yx}\, S_{xx}^{-1}\, \underline{S}_{xy} \right)(\omega)\, \frac{d\omega}{2\pi}$$

$$= \int_{-\infty}^{\infty} \left(1 - \alpha^2(\omega)\right) S_{yy}(\omega)\, \frac{d\omega}{2\pi} \qquad (6)$$

where $\alpha^2(\omega)$ is the multiple coherence and $(1 - \alpha^2(\omega))$ measures the reduction in power possible at the frequency ω. With $\alpha^2(\omega) = 1$ the mean square error is zero and with $\alpha^2(\omega) = 0$ the mean square error is just

$$\int_{-\infty}^{\infty} S_{yy}(\omega)\, \frac{d\omega}{2\pi} = R_{yy}(0) = E\,|y(t)|^2 \qquad (7)$$

which is the original power in the process y(t). Now the quantity $(1-\alpha^2(\omega))\, S_{yy}(\omega)$ represents the residual power at each frequency after the best linear estimate of the form (1) has been subtracted out. Hence the db reduction in power at each frequency is just the ratio of the output power of the residual (see equation (2)) to the input power in y(t) or

$$I_H(\omega) = 10 \log \frac{S_{ee}(\omega)}{S_{yy}(\omega)} = 10 \log (1 - \alpha^2(\omega)) \qquad (8)$$

where $\alpha^2(\omega)$ is the multiple coherence and $S_{ee}(\omega)$ is the power spectrum of the error process

$$e(t) = y(t) - \sum_{k=1}^{p} \int_{-\infty}^{\infty} h_k(\alpha)\, x_k(t-\alpha)\, d\alpha \qquad (9)$$

B. Noise Reduction Outside The Fitting Interval

We would also like to determine the noise reduction in db which would result from using a set of filters $g_k(t)$, k=1, ...,p which have been derived either from another fitting interval or from theoretical considerations. To accomplish this let $h_k(t)$ be the optimal filters for the time under investigation and let $g_k(t)$ be any other set of filters whose mean square error is to be compared with $h_k(t)$. The mean square error of the g filters can be written using the orthogonality principle as

$$E \left| y(t) - \sum_{k=1}^{p} \int_{-\infty}^{\infty} g_k(\alpha)\, x_k(t-\alpha)\, d\alpha \right|^2 =$$

$$E\left|y(t) - \sum_{k=1}^{p} \int_{-\infty}^{\infty} h_k(\alpha)x_k(t-\alpha)d\alpha + \sum_{k=1}^{p} \int_{-\infty}^{\infty} \left(h_k(\alpha) - g_k(\alpha)\right) x_k(t-\alpha)d\alpha\right|^2$$

$$= E\left|y(t) - \sum_{k=1}^{p} \int_{-\infty}^{\infty} h_k(\alpha)x_k(t-\alpha)d\alpha\right|^2 + E\left| \sum_{k=1}^{p} \int_{-\infty}^{\infty} \left(h_k(\alpha)-g_k(\alpha)\right) x_k(t-\alpha)d\alpha\right|^2$$

$$= \int_{-\infty}^{\infty} \left(1-\alpha^2(\omega)\right) S_{yy}(\omega) \frac{d\omega}{2\pi} + \int_{-\infty}^{\infty} (\underline{H} - \underline{G})^* S_{xx}(\underline{H} - \underline{G})\ (\omega) \frac{d\omega}{2\pi}$$

$$= \int_{-\infty}^{\infty} \left[\left(1 - \alpha^2(\omega)\right) + \frac{(\underline{H} - \underline{G})^* S_{xx}\ (\underline{H} - \underline{G})\ (\omega)}{S_{yy}(\omega)} \right] S_{yy}(\omega) \frac{d\omega}{2\pi} \qquad (10)$$

Hence, if we call the new error $\ell'(t)$ we have

$$\ell'(t) = y(t) - \sum_{k=1}^{p} \int g_k(\alpha)\ x_k(t-\alpha)\ d\alpha$$

with power spectrum $S_{\ell'\ell'}(\omega)$, the new value for the improvement in the $S_k(t)$ filters would be

$$I_G(\omega) = 10 \log \frac{S_{\ell'\ell'}(\omega)}{S_{yy}(\omega)} = 10 \log_S \left(1 - \alpha^2(\omega) + \frac{(\underline{H} - \underline{G})^* S_{xx}\ (\underline{H} - \underline{G})\ (\omega)}{S_{yy}(\omega)}\right)$$

(12)

Equation (12) shows that the improvement in the $g_k(t)$ filters is expressed in terms of the improvement in the hk(t) filters and a correction term which is zero when $\underline{H} = \underline{G}$.

The improvement values $I_H(w)$ and $I_G(w)$ in equations (8) and (12) are those shown in the main body of the report.

Reference

1. Papoulis, A., Probability, Random Variables, and Stochastic Processes, McGraw Hill, 1965.

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13. ABSTRACT

Multiple coherence gives a quantitative measure versus frequency of how well a linear combination of n input channels can match the (n + 1)st channel in a seismic array. If the inputs can match the output exactly, then the multiple coherence is unity and only n channels are necessary to describe the noise field. This report shows multiple coherence versus frequency at three vertical arrays of short period, vertical component seismometers. One of the seismic traces, either the surface trace or the deepest trace, is used as the output and 2 to 6 of the others are used as inputs.

The multiple coherence properties of the noise are similar at the three vertical arrays with similar geometries. At all three sites the downhole channels correlate with each other better than with the surface channel. At all three sites the coherence between downhole seismometers decreases markedly as their separation increases.

When the deep trace is the output and all seismometers are added as inputs, the multiple coherence is highest at GV-TX. The multiple coherence at GV-TX is greater than .85 for all frequencies from .1 to 2.5 cps. For the AP-OK and UBSO wells the multiple coherence varies between .6 to .9 for most frequencies greater than .5 cps.

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	ROLE	WT	ROLE	WT	ROLE	WT
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